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# Adaptive Wing Model for Wind Channel Tests

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**ABSTRACT**

The aim of this work is to realize an adaptive wind channel wing model by means of a “structronic” concept. The desired geometry changes are achieved through the use of the structural flexibility, and no moveable parts are required.

The wind channel model presents two active sections: the “bump” section, on the upper surface of the airfoil, and the adaptive trailing edge. The changes of the airfoil geometry by means of these parts of the model make possible to vary the distribution of the aerodynamic load on the wing. The activation of the bump and of the trailing edge is realized by means of solide state actuators. A sytem of ca. two hundred shape memory alloy actuators is used. The actuators give here also a contribution to the stiffness of the structure. Here the numerical results of the FEM investigations are presented, as well as the experimental results on the prototypes of the adaptive trailing edge and the bump actuators.

**INTRODUCTION**

The aerodynamic forces acting on a lifting surface depend directly on its geometry. The more control is exerted on the airfoil geometry, the more influence is gained on aerodynamics.
Aircraft designers are aware of this simple fact since the beginning of aviation history. And before them, zoologist had observed the flight of birds and insects over centuries, learning how nature chooses entire, continuous geometry control as the way of governing aerodynamics and maximize flight efficiency and safety.

Hence, why do airplanes fly with minimal geometry control? Why, even at the beginning of the 21st century, is the vision of an aircraft with full geometry adaptability, and therefore extreme efficiency and reliability, still far from reality?
During the 100 years of aviation history, a lot of changes and improvements occurred in aircraft design, in particular concerning avionics and materials. As far as geometry control is concerned, however, modern aircraft fly almost in the same way as the first ones: the relative motion of rigid surfaces (flight controls, high-lift devices, air brakes) controls very few geometric degrees of freedom. Of course, this constrains not only maneuverability but also efficiency: for most part of its service, the aircraft’s geometrical configuration is far from the optimal one.

Since the beginnings of aviation’s history scientists are looking for alternative or complementary forms of shape adaptability, with more degrees of freedom and continuous geometry changes. The first inventions concerning lifting surfaces with variable geometry date from the thirties (Hannah, 1930; Rocheville, 1932; Cone, 1939). Fifty years later the research activity in this field became very intensive, as documented by the large number of patents (Frost et al., 1981; Rowarth, 1981;

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McKinney, 1982; Statkus, 1982), and papers (Hilbig and Wagner, 1984; Renken, 1985; Szodruch, 1985; Greff, 1990) on this topic.

As a rule, the proposed approaches were extensions of the classical solution – denoted “mechatronic” - used for flight controls and high-lift devices and based on mechanisms with moveable parts and discrete forces. The fact that none of the considered concepts is implemented in a practical case testifies that this design philosophy for geometry control is not appropriate for the strict requirements of aircraft design. If realized in such a way, each additional geometry degree of freedom must be paid for in terms of weight and maintenance. This price is evidently too high compared to the advantages of extensive geometry control. As a matter of fact, at the current state of the art, the use of geometry control devices is kept at the minimum indispensable to allow flight at all.

**THE “STRUCTRONIC” APPROACH TO THE SHAPE CONTROL MATTER**

A mechanical system with moveable parts does not constitute the only possible solution for the realization of structures with variable geometry.
Deliberate use of structural flexibility (the “structronic” way) represents the more complex task from the point of view of structural design; however, the potential of such solution, concerning structural optimization and realization of continuous, multi-degree-of-freedom geometry changes is definitely higher.

Unlike a mechatronic system, which alternates high-stiffness members and elements with infinite flexibility in one or more degrees of freedom (like hinges or linear bearings), a new constraint appears in the design process of a structronic system: an upper limit for stiffness. If stiffness exceed a certain level, it will not be possible to induce the desired shape changes without reaching a critical stress level and therefore endangering the structural integrity. Even if this critical level is not reached, high stiffness requires high actuator forces and, consequently, large and heavy actuator devices.

Due to the new constraint of upper stiffness limit, joining the classical constraints of lightweight design, i.e. maximum displacement under load - which implies a lower limit for stiffness – and an upper limit for the system’s weight, the structural design process becomes a real challenge. It can be expected that in most cases, if classical materials and actuators are used, no solution exists which fulfills all the requirements. Like nearly thirty years ago, when carbon-fiber reinforced composites opened new horizons in lightweight design, the solution of the complex requirement scenario of adaptive lightweight structures will be supplied by a new material class, the so-called active, smart or multifunctional materials.

The maximum-weight and the maximum-displacement-under-load requirements are only indirectly in contrast to another, and the use of a material with high stiffness-weight ratio – like carbon-fiber reinforced composites – can widen the range of possible solutions. However, the upper stiffness limit, imposed by the adaptation task, and the lower stiffness limit of the maximum-displacement-under-load condition are directly opposite requirements, which cannot be uncoupled if a classical, passive material is used.

Only the use of an active material, a solid-state, strain induced actuator provides stiffness for the structural, load-carrying task and, at the same time, comparatively large displacements under actuation.
The features of solid-state actuators make them very attractive even for the classical lightweight structural task: when used in connection with proper controller and sensor systems, such active materials can completely suppress the displacement under

load, and consequently realize a virtually infinite stiffness/weight ratio. That means theoretically zero weight for stiffness-designed structural parts.

A further aspect of solid-state actuators, which is relevant for the use in adaptive aircraft structures, is the very high specific energy compared to classic actuator principles. Due to this feature, the structronic-based geometry adaptation system is likely to be lighter than the mechatronic one not only due to structural weight saving but also due to reduced weight of the actuator device. Moreover, multifunctional materials allow the realization of distributed actuator devices, as requested by a structure with distributed flexibility.

Among available active materials, shape memory alloys (SMA), due to their high active strain and consequently extremely high specific energy are predestined to play an essential role in the field of adaptive aircraft structures.
Shape memory alloys are thermally activated. While activation can occur relatively fast (e. g. through electrical resistance heating), the deactivation process – ruled by cooling – limits the actuator's frequency response. This aspect, which usually constitutes one of the major drawbacks of shape memory alloys, is of secondary importance in the aeronautical environment, where low outside temperatures and high convection allow faster heat transfer.

## THE GEOMETRY OF THE WING MODEL

The purpose of tests on the wind channel model is to investigate the possibility to weaken the transonic shock wave that occurs on the upper side of the wing and consequently to reduce the drag.
The model presents two active zones, the "bump" sector and the rear part of the model, usually occupied by the flap, close to the trailing edge. We will refer to this part as the adaptive trailing edge.
Below there are the geometric characteristics of the model and the position of the adaptive areas.

- Chord **c** = 400 mm
- Wingspan **b** = 1 m
- Bump region: between the 65% and the 85% of the chord.
- Adaptivetrailing edge: between the 85% and the 100%.

The wing model dimensions fit with the wind channel sizes, in order to have a two dimensional flow around the model and to reduce the three dimensional effects.

The use of the adaptive characteristics of the model allow to test a lot of different configurations of the wing, simply acting on the control system, avoiding the use of interchangeable rigid parts.
The air conditions during the wind channel tests are typical of a commercial aircraft during the cruise flight and in the high subsonic range.

- Mach number $\mathbf{M}_\infty = 0.9$
- Total pressure $\mathbf{p_0} = 140$ kPa
- Temperature $\mathbf{T} = 310$ K

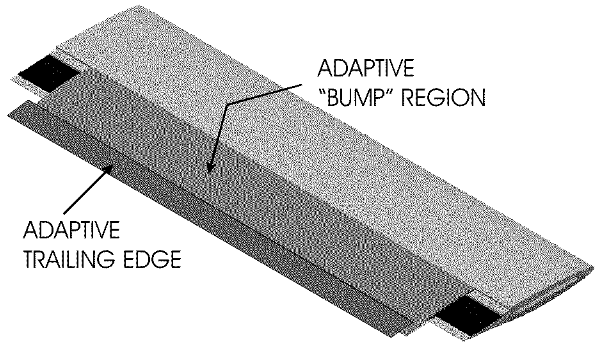



***Fig. 1: The wing model and the active areas***

**THE ADAPTIVE "BUMP" REGION**

The "bump" region extends for 80mm chordwise, and the depth of the available space for the actuators amounts to ca. 7 mm. Due to these extremely reduced space availability no practicable concept with classical actuators was found which could realize a reliable deformation independent of the spanwise position.

The maximum aerodynamic load is 47 kPa and it depends on the change of the airfoil camber.

**THE ACTUATOR FOR THE "BUMP" REGION**

The actuators for the "bump" region are driven by the force exerted by SMA wires. The passive component of the actuator is realized like a composite spring: Every spring is wrapped by a bundle of wires. The number of the wires of the bundle has been determined in order to perform the requested displacement.

The figures below show the design of the composite passive spring and the coupled spring with the wires.

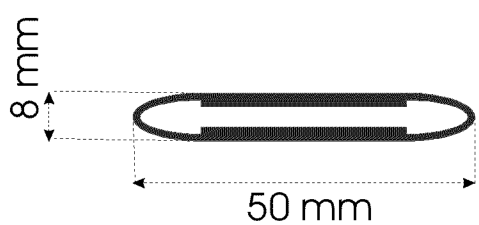



***Fig. 2: The geometry of the passive spring actuator for the "bump" region.***

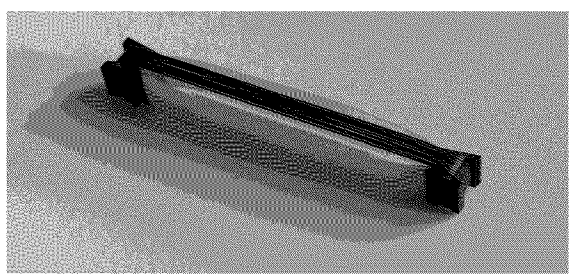


***Fig. 3: Picture of the "bump" actuator prototype***

The longitudinal force exerted by the SMA wires deforms the composite spring, enabling the vertical displacement of the upper and lower straight part of the spring. The actuator element is equipped with a bundle of 20 SMA wires, in order to achieve a vertical displacement of 2 mm.

The figure below shows the spring actuators inserted in the "bump" region. The middle, straight part of the spring elements is bonded to the outer skin and provided with high stiffness in order to avoid local deformations. Both sides of the skin have a curved profile and bend when the wires are activated, producing the desired thickness increase.

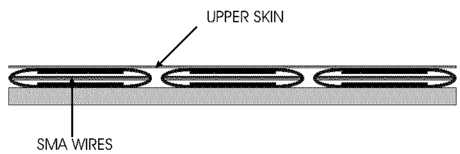



***Fig. 4: Spanwise section of the "bump" region***

## THE RESULTS OF THE TEST ON THE "BUMP" ACTUATOR

Several tests have been conducted in order to determine the longitudinal and vertical displacement as a function of the force exerted by the actuators. The figure below shows the result curves of the test. The maximum transversal displacement was well above the required displacement of 2 mm. Some of this performance reserve will be used after mounting into the bump region, since the actuator elements have to balance the additional stiffness due to the skin. The wires were heated electrically. The minimum activation current was ca. 5A, and the corresponding voltage was 1 V.

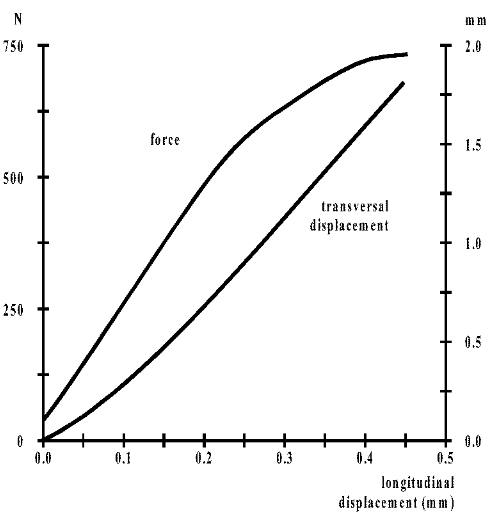



***Fig. 5: Spring characteristics of the actuator prototype***

**GEOMETRY AND DISPLACEMENTS OF THE ADAPTIVE TRAILING EDGE**

The trailing edge structure extends between the 85% and the 100% of the chord of the wing model, as already mentioned. That means a 60 mm chordwise extension of the adaptive trailing edge, and a maximum thickness at the root of 9.11 mm. The following figure shows the geometry of the adaptive structure.

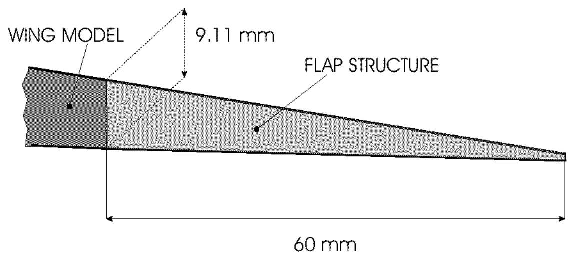



***Fig. 6: The geometry of the adaptive trailing edge***

The deflection of the adaptive trailing edge is directed either upward or downward, in order to achieve a cambering and a decambering of the wing model.

The minimum requested relative rotation of the trailing edge respect to the rest of the model is of 1° upward and of 3° downward.

The following figure shows the displacement of the tip of the trailing edge to achieve the requested rotations.

| | ROTATION | TIP DISPLACEMENT |
|---|---|---|
| UPWARD | 1 deg. | 1.05 mm |
| DOWWARD | 3 deg. | 3.145 mm |

***Fig. 7: Displacements and rotations of the tip of the wing model***

**THE AERODYNAMIC LOAD**

The aerodynamic load on the wing model depends on the deflection of the trailing edge. There are three different situations: the clean configuration, the three degrees cambered form and the one degree decambered form. The figure 8 shows the aerodynamic load on the upper and lower side of the trailing edge contour, as it has been computed in the numerical model of the structure, for the three degrees cambered configuration. With **P** we indicate the local value of the pressure respect to the adimensional coordinate **X/c** and with **p** the value of the freestream pressure.

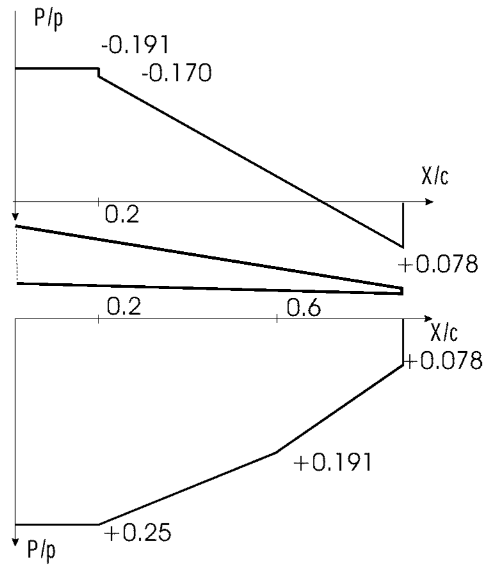



***Fig. 8: The local pressure distribution on the trailing edge for the three degrees cambered configuration.***

When the structure assumes the three degrees cambered configuration, the wing model experiences the highest aerodynamic load. The load on the wing model structure is 1300 N, that means an everage pressure of ca. 22 kPa. In the one degree decambered configuration the load is only 730 N, nearly half of the former situation.

**THE MAXIMUM DISPLACEMENT DUE TO THE AERODYNAMIC LOAD**

A very strict condition is assigned on the deformation of the adaptive structure induced by the aerodynamic load. For every load condition and every configuration assumed by the trailing edge the upper limit of the deformation is 0.1 mm.
A high stiffness structure is capable to control the deformation due to the aerodynamic load, while a low stiffness structure needs low forces exerted by the actuators to achieve the requested displacements.
Furthermore a very stiff structure could suffer high levels of strain and stress, those can bring the structure to fail.
Therefore the goal is to realize a trade off between the opposite characteristics of the adaptive structure, as will be clear in the next pages.

**THE ACTUATORS ACTION AND THE WIRES-STRUCTURE COUPLING**

The reduced dimensions of the wing model constitute one of the main problems to realize the adaptive structure. The use of solid state actuators, e.g. shape memory alloy wires, fits with the geometry of the trailing edge structure and with the purposes of the project.

The use of wireshaped actuators allows to insert them in the hollow shell structure of the model, achieving an internal actuator system. For our purposes we use Ni-Ti alloy based actuators with high transformation temperature, in order to have a quick response behavior. The diameter of the wires is 0.38 mm.

The following figure shows the coupling between the trailing edge passive structure and the SMA actuators.

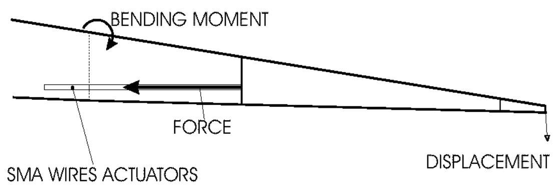



***Fig. 9: The coupling between the trailing edge passive structure and the actuators.***

The vertical stiffeners control the local deformations of the upper and lower skins. Furthermore the front stiffener connects the wires to the trailing edge structure and transfers the forces between the passive structure and the actuators. The action exerted by the wires determines a cambering bending moment that deforms downward the structure. The stored elastic energy of the deformed structure acts as "bias" effect to reactivate the memory of the material.

The use of "one way" shape memory effect actuators doesn' t allow to decamber the wing model as requested. In order to achieve also this feature of the trailing edge, a new reference configuration has been determinated, a one degree decambered configuration as new undeformed trailing edge structure. Partially heating the wires carries the structure to the clean form, the original shape of the airfoil. A further heating drives the structure through the cambered configurations up to the three degrees final feature.

As mentioned before the design of the adaptive structure should realize a trade off between a high stiffness value, in order to meet the upper bounded deformation task, and a reasonable flexibility, in order to realize the requested dispalcement.

Two possibilities have been investigated:

- A very high stiffness passive trailing edge structure, able to control the deformation under the maximum aerodynamic load , according to the request. As a consequence of this design, high actuation forces are necessary to displace the structure. Furthermore this implies high stress and high strain levels.

- A global stiffness of the adaptive trailing edge, i.e. the passive structure and the wireshaped actuators, able to match the minimum value to control the deformation due to the maximum aerodynamic load. This design allows to exert lower actuation forces and to bound the maximum values of stresses and strains.

**FINITE ELEMENT ANALYSIS OF THE ADAPTIVE TRAILING EDGE**

Through the finite element model of the trailing edge we want to analyze the 2D behavior of the structure. Exspecially we want to determine:

- The position of the vertical stiffeners inside the structure.
- The thickness of the skins.
- The number of the actuators.

Furthermore the new one degree decambered reference configuration needs to be investigated.
In the following we describe the design of the trailing edge, according to the second realization above mentioned. That design meets all the requirements of the project. At the end of this chapter can be found a comparison between the two designs of the adaptive structure.

In the actual design of the adaptive trailing edge the structural contribution of the SMA wires actuators play an essential role. This contribution allow us to determine a lighter structure and lower actuation forces as well.
An appropriate design of the cross section of the upper skin panel, together with the material selected for the analysis, determines the global and local stiffness of the airfoil in order to achieve:

- Together with the wires the required global stiffness able to bound the displacement under the maximum aerodynamic load.
- A smooth profile of the airfoil, under every aerodynamic load as well as under the actuators action.
- A "passive" stiffness, i. e. the contribution of the structure without actuators, able to stretch again the wires after activation and to reactivate the memory of the material.

The most important component of this design is the upper skin panel, between the root of the trailing edge and the inner vertical stiffener. This acts as a spring, carrying most of the aerodynamic load and provided of the right stiffness to deform under the actuators forces as required. The rest of the skin panels are designed in order to have a smooth contour of the airfoil.

The adaptive trailing edge is connected to the wing model through the extended upper skin panel. That solution avoids discontinuities in the wing profile and realizes a smooth shape. The lower skin panel is not connected with the wing model, enabling the deflection of the trailing edge structure. A double connection of the trailing edge even through the extended lower skin panel results too stiff for the purposes of the project. The position of the vertical stiffeners inside the hollow structure of the trailing edge is important to control the deformation of the panels due to the aerodynamic load. Expecially the inner stiffener performs several tasks:

- Transfers the loads between the coupled passive structure and the actuators. This should be done without appreciable derformation of the stiffener.
- The position inside the structure determines the width of the inner stiffener and the length of the wires.

The clockwise moment exerted by the actuators depends on the lever arm of the forces respect to the upper connection of the skin panel. The displacement of the application point of the forces, and as a consequence of the whole structure, depends on the length of the wires.

## THE RESULTS OF THE FINITE ELEMENT ANALYSIS

The finite element analysis has been performed with the software ANSYS version 5.4. The figure below shows the section of the finite elemet model of the trailing edge and the wires actuators.

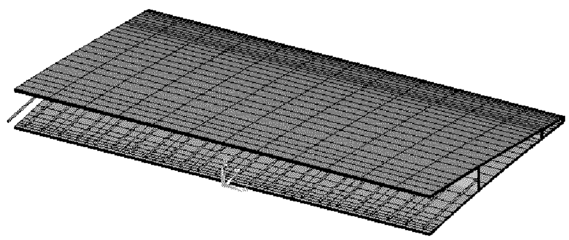


***Fig. 10: The finite element model of the trailing edge.***

The upper and lower skin panels as well as the two vertical stiffeners have been implemented with SHELL 99 elements, while the wires have been implemented with the LINK 8 elements. The design of the trailing edge structure, i.e. the optimization of the cross section of the panels, the position of the vertical stiffeners and the number of the wires, has been performed for the 0 degree cambered configuration under the maximum aerodynamic load condition experienced by the wing model. The front end of the upper skin panel is fixed in all 6 degrees of freedom: this assumption takes in count the high stiffness of the rest of the model, compared with the flexibility of the adaptive trailing edge.

The number of wires is a trade off between their contribution to the global stiffness of the adaptive structure and the force that they are able to exert to move the trailing edge. Each single wire contributes as a spring against the aerodynamic load acting on the wing model. The constant of the equivalent spring represented by the wire can be computed as:

$$K_w = EA / L$$

where E is the Young modulus of the alloy, A is the area of the section and L is the lenght of the wire. The Young modulus depends on the state of the alloy, i.e. on the temperature and on the applied load.

The upper and lower skin panels, as well as the vertical stiffeners, are carbon fiber reinforced laminates. The stacking sequence is optimizated according to the different properties of the panels.
In order to perform a linear analysis af the mechanical behavior of the wing model, and exspecially of the trailing edge structure, the new one degree decambered reference configuration has been determinated through the numerical application of opposite forces respect to the forces exerted by the actuators. For this pourpose the contribution to the global stiffness of the wires is neglected.

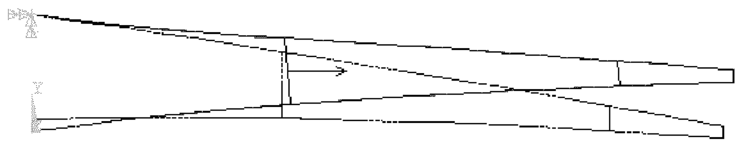


***Fig. 11: The one degree decambered reference configuration***

The finite element model has been updated according to the new reference shape. The following picture shows the new, one degree decambered, and the old reference configuration. The displacements of the following figures are not in scale.

The first step is to evaluate the deformation of the structure under the action of the aerodynamic load corresponding to the one degree decambered configuration. In this configuration the wires are in the cold state and they express the lowest Young modulus value. The following figure shows the deformation of the structure.

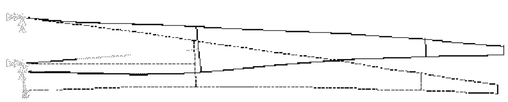


***Fig.12: The displaced new configuration: Section***

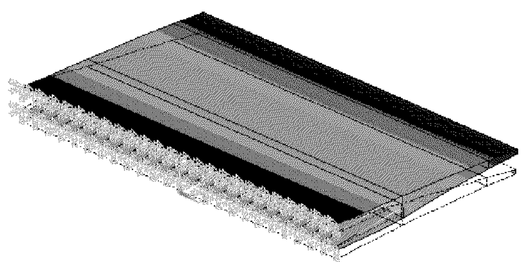


***Fig. 13: Displacements due to the aerodynamic load of the new reference configuration***

The activation of the wires in the numerical model is taken in count through forces acting in the nodes connecting the wires and the inner vertical stiffener. The next figures show the deformed section of the trailing edge and the distribution of the displacements in the structure.

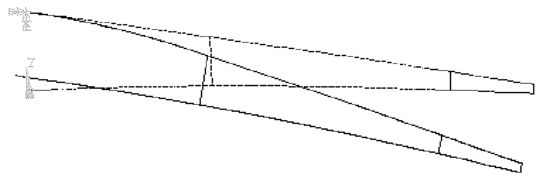


Fig: 14: Section of the displaced structure due to the action of the actuators

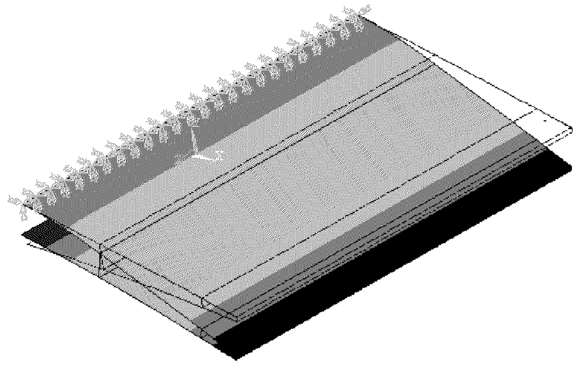


Fig. 15: The deformed structure under the action of the SMA wires

**THE COMPARISON BETWEEN THE HIGH STIFFNESS STRUCTURE AND THE LOW STIFFNESS STRUCTURE**

As mentioned before, two different approaches have been investigated to realize the adaptive structure: a very stiff passive structure, able to carry the aerodynamic load and to bound the consequently deformations, and low stiffness structure, able, with the structural help of the wires, to achieve the same task. The second solution showed better possibilities of success. We present now a brief comparison between the two structures, through the results of the ANSYS analysis. For this purpose the material is aluminium.

The comparison is made through the stiffness of the upper skin panel, i.e. the flexural rigidity D, and the forces exerted by the actuators.

Indicating with D the following quantity:

$$D = E h^3 / 12 (1 - \nu^2)$$

where h is the thickness of the panel, and with the index H and L the high and the low stiffness configuration, we have:

$D_H = 170$ Nm $\quad D_L = 31$ Nm

The forces exerted by the actuators, as a continuous distribution of wires along the wingspan, is:

$F_H = 1300$ N/ cm $\quad F_L = 250$ N/ cm

This short overview shows that the low stiffness structure is more suitable for the pourposes of this work. The reduced dimensions of the model make very difficult to insert a great number of actuators inside the structure and therefore the availability of high actuation forces.

**EXPERIMENTAL RESULTS ON THE ADAPTIVE TRAILING EDGE PROTOTYPE**

In order to test and verify the results of the numerical model and, expecially, to get some experience with this new technology, a prototype of the adaptive trailing edge with the internal actuators‘ set has been designed and built.

This prototype is slightly different from the numerical model: The main pourpose of the tests is to verify the connection between the wires and the passive structure and to verify the transfer of the forces between the actuators and the trailing edge structure. Both the upper and lower skin panels are carbon fiber reinforced laminates, according to the stacking sequences of the numerical model. The vertical inner stiffener is steelmade, instead of composite material fabrication and it is glued to the upper and lower skin panels. The prototype is lacking of the outer stiffener: During the experimental tests the adaptive structure doesn‘ t experience any aerodynamic load.

The prototype of the adaptive trailing edge extends 220 mm spanwise, and the lower skin panel extends 50 mm chordwise, in order to allow the clamping of the prototype for the tests. The figure 16 shows the prototype of the adaptive trailing edge.

For the purposes of the tests the heating of the SMA actuators has been achieved throug the Joule effect, as a consequence of the flow of an electric current in the wires.

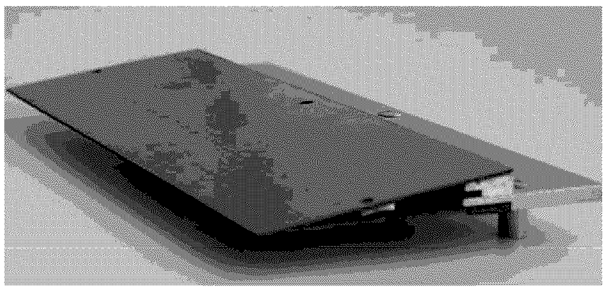
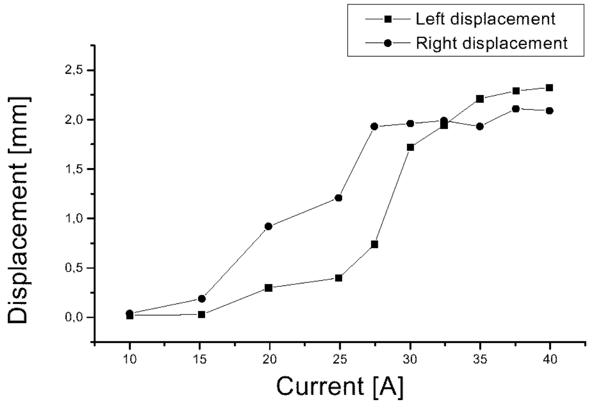


***Fig. 16: The prototype of the adaptive trailing edge***

Therefore the actuators have been connected to a current-tension generetor, able to supply up to 580 Ampere. The cooling phase is effected through the surrounding air by convection.

The actuators‘ set consists of 192 wires, joined together in 12 bundles of 16 wires each one. The following pictures show the displacement of the upper left and right corner of the tip of the trailing edge and the average value, as a function of the current and the voltage.



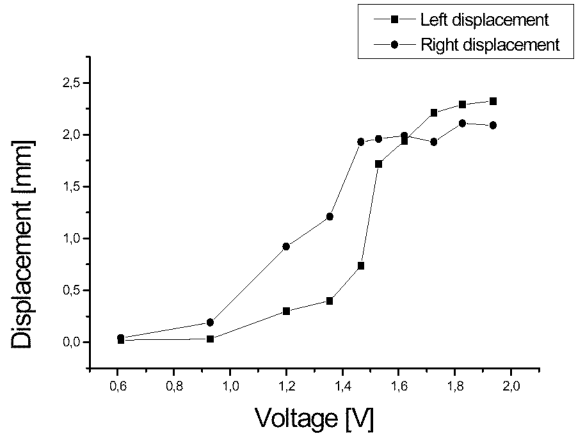




***Fig. 17: The displacement as a function of the current***

***Fig. 18: The displacement as a function of the voltage***

Unfortunately the failure of the glued connection of the metal stiffener with the upper skin panel carried the displacement of the tip of the trailing edge only up to ca. 2.5 mm. The high heat flux through the metal part, due to the heating of the wires, raised the temperature of the glued joint and reduces its strength.

## CONCLUSIONS

The features of shape memory alloys make them very attractive as actuator materials for adaptive aerospace structures. In this work the use of such a material is extended to their structural contribution: this new approach allows to actively modify the stiffness of a structure, changing the internal structure of the material and using this property as an induced strain actuator. This new aspect of designing adaptive systems presents new problems and new fascinating opportunities.

The experimental tests show the feasibility of this concept, and new tests are performed at the present time.

A more fine analysis of the coupling between structures and SMA actuators and the integration of these materials in the composite materials must be carried on, to investigate all the possibilities that this new design can offer.

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